Land surface data assimilation for Numerical Weather Prediction

P. de Rosnay, J. Muñoz Sabater, C. Albergel, G. Balsamo, A. Fouilloux, M. Dahoui, P. Lopez, L. Isaksen, J.-N. Thépaut and many other colleagues from ECMWF
Land Surface in NWP

- **Land surfaces**: Boundary conditions at the lowest level of the atmosphere

- **Land surface processes** → Continental hydrological cycle, interaction with the atmosphere on various time and spatial scales, strong heterogeneities

- Crucial for near surface weather conditions, whose high quality forecast is a key objective in NWP

- Land Surface Models (LSMs) prognostic variables include:
  - Soil moisture
  - Soil temperature
  - Snow water equivalent, snow temperature, snow density

The ECMWF Integrated Forecasting System (IFS) data assimilation system
From L. Isaksen's training courses
http://www.ecmwf.int/newsevents/training/meteorological_presentations/2013/DA2013/index.html

Data Assimilation System:
Provides best possible accuracy of initial conditions to the forecast model

- 4D-Var for atmosphere
- Land surface data assimilation
- SST and Sea Ice analysis

- Surface and upper air analyses are running separately in parallel → weakly coupled (see D.Dee pres)
- Feedbacks provided through the first guess forecast initialised with the analysed fields
Land Surface data assimilation for NWP

- **Snow depth**
  - **Approaches**: Cressman (DWD, ECMWF ERA-I), 2D Optimal Interpolation (OI) (ECMWF, Env. Canada, JMA)
  - **Observations**: SYNOP snow depth and NOAA/NESDIS snow Cover (ECMWF, UKMO)

- **Soil Moisture**
  - **Approaches**:
    - 1D Optimal Interpolation (Météo-France, Env. Canada, ALADIN and HIRLAM)
    - Analytical nudging approach (BoM)
    - Simplified Extended Kalman Filter (DWD, ECMWF, UKMO)
    - EnKF (under dvpt at Env. Canada)
  - **Conventional observations**: SYNOP data of 2m air relative humidity and air temperature; dedicated 2D OI screen level parameters analysis
  - **Satellite data**: ASCAT soil moisture (UKMO, dvpt ECMWF), SMOS (dvpt ECMWF, UKMO, Env. Canada)
Snow data assimilation

**Snow Model:** Component of H-TESSEL (Balsamo et al., JHM 2009, Dutra et al., 2010)
- Snow depth $S$ (m) (diagnostic)
- Snow water equivalent SWE (m), ie snow mass
- Snow Density $\rho_s$, between 100 and 400 kg/m$^3$

\[
SWE = \frac{S \cdot \rho_s}{1000} \quad \text{[m]}
\]

**Observations types used:**
- Conventional snow depth data: SYNOP and National networks
- Snow cover extent: NOAA NESDIS/IMS daily product (4km)

(Drusch et al. JAM, 2004)

**Data Assimilation Approaches:**
- Cressman Interpolation in ERA-Interim
- Optimal Interpolation in operations

(de Rosnay et al, Survey of Geophysics 2013)
Use of SYNOP and National Network data

National networks data:
- GTS: Sweden (>300), Romania(78), The Netherlands (33), Denmark (43), Norway (183) and since September (not on this map) Switzerland (>300)
- FTP: Hungary (61)
Use of SYNOP data

- Not much SYNOP reports in the US

- Would be valuable to have more snow depth data on the GTS (Global Telecommunication System)

→ Snow Watch initiative (part of Global Cryosphere Watch) to improve NRT snow depth data availability on the GTS
Validation data: NWS/COOP
- NWS Cooperative Observer Program
- Independent data relevant for validation
- Used to validate a set of numerical experiments considering different assimilation approaches and IMS snow cover

<table>
<thead>
<tr>
<th>Numerical Experiments</th>
<th>Bias (cm)</th>
<th>R</th>
<th>RMSE (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cressman, IMS 24 km</td>
<td>1.1</td>
<td>0.66</td>
<td>18.0</td>
</tr>
<tr>
<td>OI, IMS 4km &lt;1500m</td>
<td>-1.5</td>
<td>0.74</td>
<td>10.1</td>
</tr>
</tbody>
</table>

- Oper until Nov 2010
- ERA-Interim
- Oper since Nov 2010

Validation against ground data
→ Improvement in snow depth with the OI compared to Cressman
**Validation data: NWS/COOP**

- NWS Cooperative Observer Program
- Independent data relevant for validation

- Used to validate a set of numerical experiments considering different assimilation approaches and IMS snow cover

**RMSE (cm) for the new snow analysis**

(OI, IMS 4km except in mountainous areas)

Model-COOP RMSE, Snow Depth, figg, Winter 2010, AN time: 0/6/12/18 (Z)

Mean=10.06 cm (1653pts)
Snow Analysis in Operations

Old: Cressman → NESDIS 24km

Current: OI → NESDIS 4km

RMSE forecast (old-current)
500 hPa geopotential height
(DJF, East Asia):

Positive impact of the OI snow analysis on snow depth and atmospheric forecasts

(de Rosnay et al; SG 2013)
Snow data assimilation: further improvements

Future IFS cycle 40r1 (19 Nov 2013)
Improved use and error specifications of the IMS product

<table>
<thead>
<tr>
<th></th>
<th>IMS \ FG</th>
<th>Snow</th>
<th>No Snow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>x</td>
<td>DA</td>
<td>5cm</td>
</tr>
<tr>
<td>No Snow</td>
<td>DA</td>
<td>DA</td>
<td></td>
</tr>
</tbody>
</table>

Impact on FC Temperature

IFS cycle 40 errors:
BG: $\sigma_b = 3$ cm
SYNOP: $\sigma_{synop} = 4$ cm
IMS: $\sigma_{ims} = 8$ cm

RMSE forecast temperature
Future (40r1)–current (38r2)

Improved use of NOAA/NESDIS IMS snow
→ Small but significant
Error reduction in IFS 40r1
compared to IFS 38r2
A short history of soil moisture analysis at ECMWF

- **Nudging scheme (1995-1999)** soil moisture increments $\Delta \Theta$ ($m^3m^{-3}$):

  $\Delta \Theta = \Delta t \ D \ C_v (q^a - q^b)$

  D: nudging coefficient (constant=1.5g/Kg), $\Delta t = 6h$, q specific humidity
  Uses upper air analysis of specific humidity
  Prevents soil moisture drift in summer

- **Optimal interpolation 1D OI (1999-2010)**

  $\Delta \Theta = A \left(T^a - T^b\right) + B \left(Rh^a - Rh^b\right)$

  A and B: optimal coefficients

  OI soil moisture analysis based on a dedicated screen level parameters (T2m Rh2m) analysis

- **Simplified Extended Kalman Filter (EKF), Nov 2010-**
  - Motivated by better using T2m, RH2m
  - Opening the possibility to assimilate satellite data related to surface soil moisture.

  Drusch et al., GRL, 2009
  de Rosnay et al., QJRMS 2013
Simplified EKF soil moisture analysis

For each grid point, analysed soil moisture state vector $x_a$:

$$x_a = x_b + K (y - \mathcal{H}[x_b])$$

$x$  background soil moisture state vector,
$\mathcal{H}$ non linear observation operator
$y$  observation vector
$K$ Kalman gain matrix, fn of $\mathcal{H}$ (linearsation of $\mathcal{H}$), $B$ and $R$ (covariance matrices of background and observation errors).

Observations used:
- **Operational**: Conventional SYNOP observations (T2m, RH2m)
- **Research**: Satellite data ASCAT, SMOS

H-TESSEL LSM: Balsamo et al., JHM, 2009
EKF surface analysis: de Rosnay et al., QJRMS 2013
- Two 1-year analysis experiments using the OI and the EKF
- Reduced root zone increments (increased at surface) with the EKF compared to the OI
- EKF accounts for non-linear control on the soil moisture increments (meteorological forcing and soil moisture conditions)
- **EKF prevents undesirable and excessive soil moisture corrections**
- Consistently improves soil moisture and screen level parameters FC
- More information on EKF vs OI in: de Rosnay et al., QJRMS 2013
Evaluation of the EKF soil moisture in the current IFS
Impact on near surface weather parameter forecasts

Two experiments:
- CTRL: current operational configuration
- Test no EKF: switch off EKF SM analysis
- Evaluation on temperature and humidity forecasts

Positive values: Larger errors when soil moisture is not analysed compared to the CTRL oper config (with EKF SM analysis)

→ Positive impact of EKF soil moisture analysis on humidity & temperature, Significant at 1000 hPa, day 1-3 (NH)
Satellite data for NWP soil moisture analysis

Active microwave data:
ASCAT: Advanced Scatterometer
C-band (5.6GHz)
NRT Surface soil moisture
Operational product
→ ensured operational continuity

Passive microwave data:
SMOS: Soil Moisture & Ocean Salinity
L-band (1.4 GHz)
NRT Brightness Temperature
Dedicated soil moisture mission
→ Strongest sensitivity to soil moisture

Operational Monitoring of surface soil moisture related satellite data:
ASCAT soil moisture (m$^3$m$^{-3}$)
SMOS Brightness temperature (K)

Stdev FG_depar
Sept. 2013
**ECMWF SMOS forward operator and Bias correction**

**SMOS forward operator:** Community Microwave Emission Modelling Platform (CMEM)

**CDF-matching** matches mean and variance of two distributions

\[ TB^*_{SMOS} = a + b \cdot TB_{SMOS} \]

with  
\[ a = TB_{CMEM} - TB_{SMOS} \left( \frac{\sigma_{CMEM}}{\sigma_{SMOS}} \right) \]

\[ b = \frac{\sigma_{CMEM}}{\sigma_{SMOS}} \]

→ Matches mean and variance

---

de Rosnay et al., in prep
ECMWF SMOS forward operator and Bias correction

SMOS forward operator: Community Microwave Emission Modelling Platform (CMEM)

CDF-matching matches mean and variance of two distributions

$$TB^{*}_{SMOS} = a + b \ TB_{SMOS}$$

with $a = TB_{CMEM} - TB_{SMOS} \ (\sigma_{CMEM}/\sigma_{SMOS})$

$b = \sigma_{CMEM}/\sigma_{SMOS}$

$\rightarrow$ Matches mean and variance

Evaluation for July 2012 $\rightarrow$

de Rosnay et al., in prep
SMOS Soil Moisture increments (mm)

July-2011 → SMOS contribution compared to oper config

July-2011 → T2m sensitivity

RMSE of forecast relative humidity
EKF without SMOS – EKF with SMOS

- Preliminary results show positive impact of SMOS assimilation
- On-going improvements in error structure

SM increments due to assimilation of SMOS data have an impact on T2m
ASCAT data assimilation

- Satellite data: surface soil moisture (top cm of soil)
- Space Agencies rely on DA approaches to retrieve root zone soil moisture

Operational since Jul. 2012

ECMWF Atmospheric conditions

SYNOP
T2m RH2m

ASCAT Surface SM

EKF Soil Moisture Analysis

SM-DAS-2: Root zone Soil Moisture Profile

ASCAT seasonal Bias correction based on CDF-matching

http://hsaf.meteoam.it/soil-moisture.php
Validation with in situ soil moisture data

International Soil Moisture Network

Validation for 2012 of ASCAT, SMOS and SM-DAS-2

For each station, time series are compared
Validation with in situ soil moisture data (USCRN)

Correlation [-]
(for stations with significant values)

<table>
<thead>
<tr>
<th></th>
<th>SM-DAS-2</th>
<th>ASCAT</th>
<th>SMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.67</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>(104 stations)</td>
<td>(104 stations)</td>
<td>(84 stations)</td>
<td></td>
</tr>
</tbody>
</table>
## Validation with in situ soil moisture data

All products expressed as soil moisture index (no unit)

<table>
<thead>
<tr>
<th>Normalized Product (stations with significant R)</th>
<th>SM-DAS-2 (310)</th>
<th>ASCAT (291)</th>
<th>SMOS (234)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation on Anomaly</td>
<td>0.56</td>
<td>0.41</td>
<td>0.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normalized Product (stations with significant R)</th>
<th>SM-DAS-2 (333)</th>
<th>ASCAT (322)</th>
<th>SMOS (258)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation</td>
<td>0.68</td>
<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
<td>Bias (In Situ - Product)</td>
<td>-0.084</td>
<td>-0.005</td>
<td>0.027</td>
</tr>
<tr>
<td>RMSD</td>
<td>0.120</td>
<td>0.110</td>
<td>0.105</td>
</tr>
</tbody>
</table>

- SMOS and ASCAT surface soil moisture have similar quality
- Assimilated product (SM-DAS-2) has a larger bias, but in terms of dynamics it shows the best agreement with in situ soil moisture data
Summary

• Different methods used by different NWP centres for snow depth (Cressman, 2D-OI) and soil moisture (1D-OI, nudging, EKF) analyses

• Snow analysis:
  • Importance of in situ data, combined with snow cover products
  • Snow watch initiative to encourage the WMO MS to make snow depth in situ data available on the GTS
  • Strong positive impact of the OI on snow depth and on atmospheric forecasts

• Soil Moisture analysis:
  • Rely on T2m and RH2m dedicated analysis
  • EKF improves soil moisture and screen level analysis and forecasts
  • Land data assimilation used in the HRES and EDA systems at ECMWF
Summary

• Use of satellite data for soil moisture analysis:
  • ASCAT & SMOS oper data assimilation in development at ECMWF, Env. Canada
  • ASCAT and SMOS operational monitoring at ECMWF
  • ASCAT operational data assimilation → SM-DAS-2 root zone profile (EUMETSAT)
  • SMOS data assimilation
    → requires microwave emission model as forward operator
    → encouraging preliminary results
• Validation: similar quality of SMOS and ASCAT soil moisture products, best performances from assimilated soil moisture products

Next steps

• Improve error specifications for SMOS and ASCAT data assimilation
• Offline LDAS development (Jacobians and Observations handling), increase coupling flexibility with 4D-Var
• Use future SMAP (Soil Moisture Active and Passive) NASA mission to be launched in 2014
Thank you for your attention!

Contact: Patricia.Rosnay@ecmwf.int

Further information: http://www.ecmwf.int/research/data_assimilation/land_surface/


